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Enantioselective β-Boration of Acyclic Enones by a [2.2]Paracyclophane-Based N-Heterocyclic Carbene Copper(I) Catalyst

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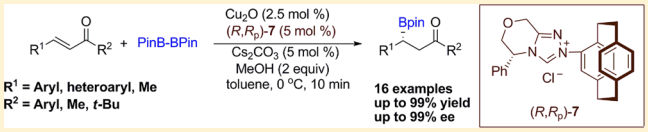
Supporting Information

ABSTRACT: A new planar and centrally chiral bicyclic 1,2,4-triazolium salt has been synthesized from [2.2]paracyclophane and phenylglycinol. The N-heterocyclic carbene (NHC) copper(I) complex generated in situ by the reaction of the triazolium salt and Cu_2O was an efficient catalyst for the asymmetric β-boration of acyclic enones, producing β-boryl ketones in high yields and enantioselectivities.



The preparation of chiral organoboron compounds remains an active area of research in chemical synthesis because the C−B bond can be converted into a wide variety of functional groups without loss of enantiopurity.[1] In the past few years, various methods have been devised for the synthesis of these compounds.[2] The most common access to α-chiral organoboron compounds is asymmetric conjugate addition of diboron reagents to α,β-unsaturated compounds, and a variety of catalytic systems have been developed.[3] Nonetheless, designing an efficient chiral ligand to meet the needs of the conjugate boration reaction in good yield and enantioselectivity is still a challenge.

Catalysis mediated by NHCs and their metal complexes has emerged as a powerful tool for asymmetric synthesis because these catalysts have several significant advantages over their phosphine counterparts.[4] The first attempt to catalyze the asymmetric β-boration of α,β-unsaturated carbonyl compounds by an NHC complex was made by Fernández and co-workers.[5] Since then, many groups have studied copper complexes of NHCs in asymmetric conjugate boration reactions.[6] Recently, a very significant development from the group of Hoveyda used NHCs in an enantioselective metal-free conjugate boration reaction.[7] Despite the fact that many exciting results have been achieved, most of them were obtained with harsh conditions, such as low reaction temperatures and long reaction times. Very recently, our group identified a planar and centrally chiral bicyclic triazolium ligand which induced exceptional enantioselectivities in the copper(I)-mediated β-boration of α,β-unsaturated *N*-acyloxazolidinones.[8] But the catalyst system induced the β-boration of α,β-unsaturated acyclic enones in only moderate enantioselectivity. In our quest to develop an efficient catalyst for the asymmetric conjugate boration reaction, we therefore report another bicyclic triazolium ligand based on [2.2]paracyclophane and its applications in the asymmetric copper(I)-catalyzed β-boration of α,β-unsaturated acyclic enones.

To begin our study, chalcone **1a** was used as a model substrate. With 5 mol % of chiral triazolium salt (S,S_p)-**3**, 2.5 mol % of Cu_2O, 5 mol % of Cs_2CO_3, 1.1 equiv of B_2Pin_2, 1.0 equiv of **1a**, and 2 equiv of MeOH in THF, the desired boration reaction proceeded rapidly at 0 °C affording product **2a** in 95% yield and 72% ee (Table 1, entry 1). However, the chiral triazolium salt (S,R_p)-**3** gave the boration product **2a** in 90% yield but in only 34% ee (Table 1, entry 2). Disappointed with these results, we screened similar chiral triazolium salts **4a−d** derived from L-pyroglutamic acid which have been successfully used in asymmetric organocatalytic reactions.[9] It was found that ligands **4a−c** catalyzed the reaction of **1a** and B_2Pin_2 only in moderate enantioselectivities (Table 1, entries 3−5). Improved enantioselectivity was obtained with ligand **4d** (Table 1, entry 6), but the result was still not satisfactory. Then, we tested amino-indanol derived triazolium salts **5a−c**[10] and phenylglycinol derived triazolium salt **6a−b**[11] as the ligand. We were pleased to find that the reaction afforded improved enantioselectivity (83% ee) with ligand **6a** (Table 1, entry 10). As shown in previous reports, planar chiral [2.2]paracyclophane has attracted considerable interest in asymmetric catalysis.[12] We were interested to see if introduction of a planar chiral [2.2]paracyclophane at the N1 position could enhance the enantioselectivity in the asymmetric conjugate boration reaction. Then we synthesized triazolium salts (R,R_p)-**7** and (R,S_p)-**7** and tested them in the β-boration of chalcone. To our delight, the boration product **2a** was obtained in 97% ee and 92% ee, respectively, with the same absolute configuration (Table 1, entries 12−13). The results indicated that the diastereomers (R,S_p)-**7** showed similar catalytic capability compared to (R,R_p)-**7**. Interestingly, the chiral triazolium salt $(R,R_p)/(R,S_p)$-**7** derived from racemic 4-formohydrazino[2.2]-paracyclophane hydrochloride also afforded high enantioselectivity (93% ee). A screening of ligand **7** showed that the absolute configuration of product **2a** was determined by the central chirality of the triazolium salts **7** and the planar chirality is immaterial. To obtain a better yield and enantioselectivity, we

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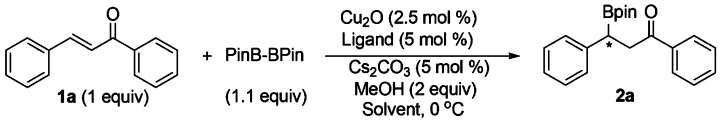
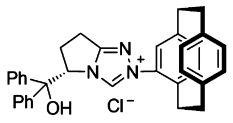
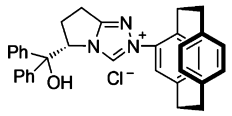
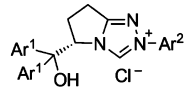
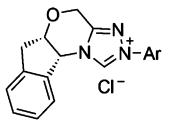
Table 1. Screening of the Reaction Conditions[a]

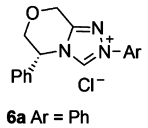


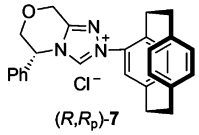

(S,Sp)-3

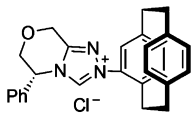

(S,Rp)-3

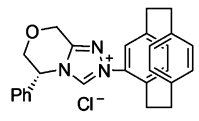

4a $Ar^1 = Ar^2 = Ph$
4b $Ar^1 = Ph$, $Ar^2 = 2,4,6\text{-}Me_3C_6H_2$
4c $Ar^1 = 3,5\text{-}(CF_3)_2C_6H_3$, $Ar^2 = 4\text{-}MeOC_6H_4$
4d $Ar^1 = 3,5\text{-}(CF_3)_2C_6H_3$, $Ar^2 = Ph$


5a Ar = Ph
5b Ar = 2,4,6-$Me_3C_6H_2$
5c Ar = 3,5-$(CF_3)_2C_6H_3$


6a Ar = Ph
6b Ar = 2,4,6-$Me_3C_6H_2$


(R,Rp)-7


(R,Sp)-7


(R,Rp)/(R,Sp)-7

entry	ligand	solvent	time (min)	yield (%)	ee (%)[b]
1	(S,S_p)-**3**	THF	20	95	72(*R*)
2	(S,R_p)-**3**	THF	30	90	34(*R*)
3	**4a**	THF	20	95	45(*R*)
4	**4b**	THF	40	89	12(*S*)
5	**4c**	THF	20	93	67(*R*)
6	**4d**	THF	40	85	76(*R*)
7	**5a**	THF	20	91	80(*R*)
8	**5b**	THF	20	92	37(*R*)
9	**5c**	THF	20	89	64(*R*)
10	**6a**	THF	20	96	83(*R*)
11	**6b**	THF	20	94	38(*R*)
12	(R,R_p)-7	THF	15	97	97(*R*)
13	(R,S_p)-7	THF	20	92	92(*R*)
14	$(R,R_p)/(R,S_p)$-7	THF	20	94	93(*R*)
15	(R,R_p)-7	toluene	10	99	98(*R*)
16	(R,R_p)-7	Et_2O	60	81	95(*R*)
17	(R,R_p)-7	CH_2Cl_2	40	91	97(*R*)
18	(R,R_p)-7	dioxane	40	83	95(*R*)

[a]The reaction was carried out with ligand (5 mol %), Cu_2O (2.5 mol %), Cs_2CO_3 (5 mol %), B_2Pin_2 (0.11 mmol), **1a** (0.1 mmol), and MeOH (0.2 mmol) in solvent (1 mL) at 0 °C. [b]Determined by HPLC analysis using a chiral stationary phase (Chiralpak IA column).

then investigated the impact of solvent on the boration reaction with triazolium salt (R,R_p)-7 as the optimal ligand. The solvent effect study showed that toluene was the best among the solvents tested (99% yield, 98% ee, Table 1, entry 15). Hence, we chose the ligand (R,R_p)-7 and the solvent toluene as the optimal conditions.

With the optimized reaction conditions in hand, a range of *α,β*-unsaturated enones were screened for the reaction (Table 2). It appears that substituents on the aromatic rings of the unsaturated enones have little effect on the reactivity and enantioselectivity (Table 2, entries 1−12). Moreover, a heteroaryl group was also tolerated and gave the corresponding compound **2m** in good yield (92%) and enantioselectivity (96% ee). The scope was also extended to alkyl-substituted *α,β*-unsaturated enones. When a methyl group was introduced at the *β*-position of the *α,β*-unsaturated enone, the corresponding product was obtained in good yield (88%) and enantioselectivity (95% ee). However, the enone with a methyl group at the carbonyl carbon gave the *β*-boryl ketone **2o** in only moderate enantioselectivity (47% ee). In order to test the hindrance effect, a relatively hindered moiety, the *t*-Bu group, was introduced at the carbonyl carbon which gave the *β*-boryl ketone **2p** in good yield (94%) and enantioselectivity (97% ee). The different enantioselectivities of *β*-boryl ketone **2n−p** demonstrated that when an alkyl group is introduced at the carbonyl carbon position of the *α,β*-unsaturated enone, the steric hindrance of the alkyl group could affect the enantioselectivity.

To further demonstrate the applicability of our catalytic process, a gram-scale reaction was attempted with only 0.1 mol

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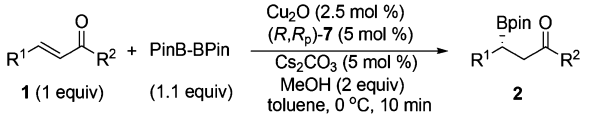
Table 2. Investigating the Substrate Scope of the Reaction[a]

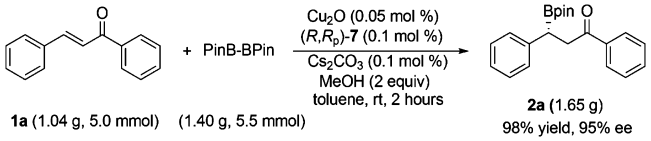


entry	R^1	R^2	yield (%)	ee (%)[b]
1	Ph	Ph	99(**2a**)	98
2	2-ClC_6H_4	Ph	97(**2b**)	97
3	3-ClC_6H_4	Ph	93(**2c**)	95
4	4-ClC_6H_4	Ph	98(**2d**)	97
5	2-$MeOC_6H_4$	Ph	95(**2e**)	99
6	3-$MeOC_6H_4$	Ph	96(**2f**)	95
7	4-$MeOC_6H_4$	Ph	95(**2g**)	97
8	4-MeC_6H_4	Ph	98(**2h**)	97
9	1-Naphthyl	Ph	97(**2i**)	98
10	Ph	4-FC_6H_4	99(**2j**)	97
11	Ph	4-$MeOC_6H_4$	97(**2k**)	95
12	Ph	4-MeC_6H_4	96(**2l**)	97
13	2-Furyl	Ph	92(**2m**)	96
14	Me	Ph	88(**2n**)	95
15	Ph	Me	93(**2o**)	47
16	Ph	*t*Bu	94(**2p**)	97

[a]The reaction was carried out with (R,R_p)-**7** (5 mol %), Cu_2O (2.5 mol %), Cs_2CO_3 (5 mol %), B_2Pin_2 (0.11 mmol), **1** (0.1 mmol), and MeOH (0.2 mmol) in toluene (1 mL) at 0 °C. [b]Determined by HPLC analysis using a chiral stationary phase (Chiralpak IA column).

% of (R,R_p)-**7** at room temperature. Under these conditions, the reaction was completed in 2 h and gave the *β*-boryl ketone **2a** in 98% yield and 95% enantioselectivity (Scheme 1), which is the most effective catalysis ever reported in an asymmetric boron conjugate addition reaction under mild conditions.[6a]

Scheme 1. Asymmetric *β*-Boration of 1a on a Gram Scale



According to the X-ray structure of (R,R_p)-**7** (see Supporting Information) and the absolute configuration of the product, a postulated model of the transition state is depicted in Figure 1.

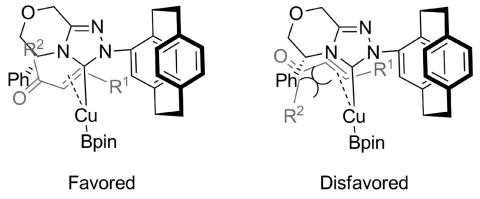


Figure 1. Postulated model of transition states.

The exceptional enantioselectivity is rationalized by avoiding the steric collision with the R^2 group in the favored transition state. The poor enantioselectivity of product **2o** could also be explained by the small hindered methyl group at the carbonyl carbon.

In conclusion, although asymmetric conjugate boration reactions have been well established, we found that [2.2]-paracyclophane-based 1,2,4-triazolium copper complexes are capable of promoting the desired enantioselective *β*-boryl ketones under mild conditions. Our designed triazolium salts behaved as powerfully as the triazolium salts used in organocatalytic processes.[13] Another improvement over the literature benchmark is that the reaction time was short, and scale-up to a gram quantity using only 0.1 mol % catalyst at room temperature could give the product in nearly quantitative yield and excellent enantioselectivity (95% ee).

EXPERIMENTAL SECTION

Triazolium salt **6b** was synthesized following a reported procedure.[11b]

Triazolium Salt 6b. White solid: Mp 118−120 °C, $[\alpha]_D^{20}$ = −82.0 (*c* 0.5, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) *δ* 10.82 (s, 1H), 7.56 (dd, *J* = 6.4, 2.9 Hz, 2H), 7.49−7.35 (m, 3H), 6.98 (s, 2H), 6.83 (s, 1H), 5.33 (d, *J* = 16.3 Hz, 1H), 5.12 (d, *J* = 16.3 Hz, 1H), 4.57 (dd, *J* = 12.7, 4.1 Hz, 1H), 4.35 (dd, *J* = 12.7, 2.4 Hz, 1H), 2.33 (s, 3H), 2.09 (s, 6H)); ^{13}C NMR (75 MHz, $CDCl_3$) *δ* 149.5, 144.9, 142.2, 136.6, 134.9, 131.0, 129.8, 129.7, 129.5, 127.4, 69.2, 62.0, 58.4, 21.2, 17.6; HRMS (ESI-TOF) calcd for $C_{20}H_{22}N_3O$ $(M - Cl)^+$, 320.1757; found: 320.1795.

General Procedure for the Synthesis of Triazolium Salt 7. To a solution of iminoether[11] (191 mg, 1.0 mmol) in MeOH (4 mL) was added 4-formohydrazino[2.2]paracyclophane hydrochloride[8] (303 mg, 1.0 mmol) at room temperature. The mixture was warmed to 50 °C and stirred for 2 h. Then solvent was evaporated under reduced pressure, and trimethyl orthoformate (4 mL) was added to the residue. The reaction mixture was stirred for 5 h at 100 °C. After completion (monitored by TLC), the solvent was removed in vacuo and the residue was purified by flash column chromatography (CH_2Cl_2/MeOH = 20/1) to afford the product as a white solid.

Triazolium Salt (R,R_p)-7. White solid: 413 mg, 93% yield, mp 218−220 °C; $[\alpha]_D^{20}$ = −147.0 (*c* 0.5, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) *δ* 11.14 (s, 1H), 7.63 (d, *J* = 3.9 Hz, 2H), 7.51−7.37 (m, 3H), 6.92 (d, *J* = 6.9 Hz, 1H), 6.87−6.47 (m, 7H), 5.37 (d, *J* = 16.1 Hz, 1H), 5.20 (d, *J* = 16.2 Hz, 1H), 4.61 (d, *J* = 13.0 Hz, 1H), 4.35 (d, *J* = 11.8 Hz, 1H), 3.40−2.87 (m, 8H); ^{13}C NMR (75 MHz, $CDCl_3$) *δ* 149.6, 142.7, 142.2, 139.4, 139.3, 137.4, 136.9, 135.9, 134.0, 133.8, 133.5, 132.9, 132.6, 130.6, 129.5, 129.3, 127.5, 127.1, 68.9, 62.1, 58.3, 35.1, 34.7, 34.7, 32.5; HRMS (ESI-TOF) calcd for $C_{27}H_{26}N_3O$ $(M - Cl)^+$, 408.2076; found, 408.2066.

Triazolium Salt (R,S_p)-7. White solid: 395 mg, 89% yield, mp 230−232 °C; $[\alpha]_D^{20}$ = +75.0 (*c* 0.3, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$) *δ* 11.14 (s, 1H), 7.73 (dd, *J* = 7.9, 1.5 Hz, 2H), 7.51−7.33 (m, 3H), 7.02 (d, *J* = 1.5 Hz, 1H), 6.86−6.46 (m, 6H), 6.26 (dd, *J* = 7.9, 1.8 Hz, 1H), 5.38 (d, *J* = 16.3 Hz, 1H), 5.17 (d, *J* = 16.3 Hz, 1H), 4.52 (dt, *J* = 29.0, 8.2 Hz, 2H), 3.85−3.64 (m, 1H), 3.30−2.91 (m, 6H), 2.7−2.62 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) *δ* 149.5, 143.0, 142.9, 139.6, 139.0, 137.2, 136.5, 135.8, 134.2, 133.5, 133.3, 132.9, 132.5, 129.9, 129.6, 128.8, 127.6, 127.3, 68.9, 62.1, 58.3, 35.0, 34.8, 34.7, 32.5; HRMS (ESI-TOF) calcd for $C_{27}H_{26}N_3O$ $(M - Cl)^+$, 408.2076; found, 408.2079.

General Procedure for the Copper-Catalyzed *β*-Boration of *α,β*-Unsaturated Enones. Under an argon atmosphere, triazolium salt **7** (2.22 mg, 5×10^{-3} mmol) and Cu_2O (0.35 mg, 2.5×10^{-3} mmol) were added to 1.0 mL of anhydrous THF in an oven-dried Schlenk flask. The mixture was stirred at 60 °C overnight to give a yellow solution of the Cu complex. Then the solvent was evaporated under argon at 80 °C, and 1.0 mL of anhydrous toluene was added at room temperature. Cs_2CO_3 (1.6 mg, 5×10^{-3} mmol) and bis(pinacolato)diboron (27.9 mg, 0.11 mmol) were added consecutively. The mixture was stirred at room temperature for 5 min and cooled to 0 °C. Then *α,β*-unsaturated enones (0.1 mmol) and MeOH (8 *μ*L, 0.2 mmol) were added simultaneously to the stirred mixture. After the mixture was stirred for 10 min at 0 °C, the solvent was removed in vacuum and the crude product was purified by flash column chromatography to afford the corresponding product **2**.

(*R*)-1,3-Diphenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propan-1-one (2a). Colorless oil: 33.3 mg, 99% yield, 98% ee; $[\alpha]_D^{20}$ = −19.2 (*c* 0.2, $CHCl_3$). The enantiomeric excess was

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determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (50:1); flow rate = 0.5 mL/min; t_R = 9.0 min (*S*, minor); t_R = 10.0 min (*R*, major). Other spectra and properties data matched those reported in the literature.[6c]

(*R*)-3-(2-Chlorophenyl)-1-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propan-1-one (2b). Colorless oil: 35.9 mg, 97% yield, 98% ee; $[\alpha]_D^{20}$ = +17.5 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (200:1); flow rate = 0.5 mL/min; t_R = 15.8 min (minor), t_R = 16.9 min (major); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.99−7.89 (m, 2H), 7.52 (ddd, *J* = 6.5, 3.8, 1.2 Hz, 1H), 7.42 (ddd, *J* = 7.1, 4.8, 2.7 Hz, 3H), 7.33 (dd, *J* = 7.8, 1.5 Hz, 1H), 7.17 (td, *J* = 7.5, 1.5 Hz, 1H), 7.09 (td, *J* = 7.6, 1.8 Hz, 1H), 3.51−3.41 (m, 2H), 3.34−3.24 (m, 1H), 1.28 (s, 6H), 1.22 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 199.3, 140.1, 136.8, 134.3, 132.9, 130.6, 129.6, 128.5, 128.1, 127.1, 126.8, 83.6, 41.6, 24.7, 24.6, 24.5; HRMS (ESI-TOF) calcd for $C_{21}H_{24}BClO_3$ $(M + H)^+$, 371.1585; found, 371.1582.

(*R*)-3-(3-Chlorophenyl)-1-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propan-1-one (2c). Colorless oil: 34.5 mg, 93% yield, 95% ee; $[\alpha]_D^{20}$ = −75.5 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (50:1); flow rate = 0.5 mL/min; t_R = 13.0 min (minor); t_R = 17.3 min (major); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.02−7.91 (m, 2H), 7.61−7.50 (m, 1H), 7.44 (t, *J* = 7.5 Hz, 2H), 7.30 (s, 1H), 7.24−7.10 (m, 3H), 3.47 (qd, *J* = 18.3, 7.9 Hz, 2H), 2.78 (dd, *J* = 10.4, 5.3 Hz, 1H), 1.25 (s, 6H), 1.17 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 199.3, 144.2, 136.6, 134.2, 133.1, 129.7, 128.5, 128.4, 128.1, 126.6, 125.8, 83.5, 42.9, 26.9, 24.6, 24.5; HRMS (ESI-TOF) calcd for $C_{21}H_{24}BClO_3$ $(M + H)^+$, 371.1585; found, 371.1574.

(*R*)-3-(4-Chlorophenyl)-1-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propan-1-one (2d). Colorless oil: 36.3 mg, 98% yield, 97% ee; $[\alpha]_D^{20}$ = −28.2 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (10:1); flow rate = 0.5 mL/min; t_R = 10.4 min (minor); t_R = 12.4 min (major). Other spectra and properties data matched those reported in the literature.[3f]

(*R*)-3-(2-Methoxyphenyl)-1-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propan-1-one (2e). Colorless oil: 34.8 mg, 95% yield, 99% ee; $[\alpha]_D^{20}$ = −92.5 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (200:1); flow rate = 0.5 mL/min; t_R = 26.1 min (minor); t_R = 27.1 min (major). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.92 (dd, *J* = 5.3, 3.4 Hz, 2H), 7.55−7.45 (m, 1H), 7.44−7.35 (m, 2H), 7.28 (dd, *J* = 7.4, 1.7 Hz, 1H), 7.13 (td, *J* = 7.8, 1.7 Hz, 1H), 6.85 (ddd, *J* = 11.7, 9.1, 4.6 Hz, 2H), 3.79 (s, 3H), 3.48 (dd, *J* = 18.0, 8.6 Hz, 1H), 3.30 (dd, *J* = 18.0, 6.1 Hz, 1H), 3.12 (dd, *J* = 8.5, 6.1 Hz, 1H), 1.26 (s, 6H), 1.20 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 200.1, 157.1, 137.2, 132.6, 130.9, 130.4, 128.3, 128.05, 126.8, 120.6, 110.2, 83.3, 55.1, 41.5, 24.8, 24.6, 21.1; HRMS (ESI-TOF) calcd for $C_{22}H_{27}BO_4$ $(M + H)^+$, 367.2081; found, 367.2082.

(*R*)-3-(3-Methoxyphenyl)-1-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propan-1-one (2f). Colorless oil: 35.2 mg, 96% yield, 95% ee; $[\alpha]_D^{20}$ = +22.5 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (50:1); flow rate = 0.5 mL/min; t_R = 17.7 min (minor); t_R = 24.2 min (major); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.96 (dd, *J* = 5.2, 3.3 Hz, 2H), 7.60−7.49 (m, 1H), 7.49−7.38 (m, 2H), 7.20 (t, *J* = 7.9 Hz, 1H), 6.88 (dd, *J* = 8.0, 5.3 Hz, 2H), 6.76−6.68 (m, 1H), 3.79 (s, 3H), 3.62−3.36 (m, 2H), 2.78 (dd, *J* = 10.8, 5.1 Hz, 1H), 1.25 (s, 6H), 1.17 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 199.7, 159.6, 143.6, 136.8, 132.9, 129.4, 128.5, 128.1, 120.8, 113.9, 111.2, 83.4, 55.1, 43.3, 27.3, 24.6. HRMS (ESI-TOF) calcd for $C_{22}H_{27}BO_4$ $(M + H)^+$, 367.2081; found, 367.2082.

(*R*)-3-(4-Methoxyphenyl)-1-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propan-1-one (2g). Colorless oil: 34.8 mg, 95% yield, 97% ee; $[\alpha]_D^{20}$ = −16.5 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (10:1); flow rate = 0.5 mL/min; t_R = 11.7 min (minor); t_R = 13.8 min (major). Other spectra and properties data matched those reported in the literature.[3f]

(*R*)-1-Phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-3-*p*-tolylpropan-1-one (2h). Colorless oil: 34.3 mg, 98% yield, 97% ee; $[\alpha]_D^{20}$ = −25.0 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (50:1); flow rate = 0.5 mL/min; t_R = 14.5 min (minor); t_R = 18.6 min (major). Other spectra and properties data matched those reported in the literature.[6c]

(*R*)-3-(Naphthalen-1-yl)-1-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propan-1-one (2i). Colorless oil: 37.5 mg, 97% yield, 98% ee; $[\alpha]_D^{20}$ = −45.0 (*c* 0.3, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (200:1); flow rate = 0.5 mL/min; t_R = 23.8 min (minor); t_R = 27.8 min (major). Other spectra and properties data matched those reported in the literature.[6c]

(*R*)-1-(4-Fluorophenyl)-3-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propan-1-one (2j).[3f] Colorless oil: 35.1 mg, 99% yield, 97% ee; $[\alpha]_D^{20}$ = −14.4 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (25:1); flow rate = 0.5 mL/min; t_R = 12.1 min (minor), t_R = 15.2 min (major); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.05−7.93 (m, 2H), 7.36−7.27 (m, 4H), 7.22−7.03 (m, 3H), 3.52 (dd, *J* = 18.2, 10.7 Hz, 1H), 3.37 (dd, *J* = 18.2, 5.2 Hz, 1H), 2.79 (dd, *J* = 10.7, 5.1 Hz, 1H), 1.24 (s, 6H), 1.16 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 198.1, 167.4 (d, *J* = 252.7 Hz), 141.8, 133.3 (d, *J* = 3.0 Hz), 130.7 (d, *J* = 9.2 Hz), 128.5, 128.4, 125.6, 115.7 (d, *J* = 21.7 Hz), 83.4, 43.1, 27.3, 24.6, 24.5; HRMS (ESI-TOF) calcd for $C_{21}H_{24}BFO_3$ $(M + H)^+$, 355.1881; found, 355.1887.

(*R*)-1-(4-Methoxyphenyl)-3-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propan-1-one (2k).[3f] Colorless oil: 35.5 mg, 97% yield, 95% ee; $[\alpha]_D^{20}$ = −58.3 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (50:1); flow rate = 0.5 mL/min; t_R = 23.9 min (minor); t_R = 35.9 min (major); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.00−7.88 (m, 2H), 7.34−7.26 (m, 4H), 7.21−7.10 (m, 1H), 6.96−6.85 (m, 2H), 3.86 (s, 3H), 3.44 (qd, *J* = 18.1, 8.0 Hz, 2H), 2.77 (dd, *J* = 10.7, 5.3 Hz, 1H), 1.24 (s, 6H), 1.16 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 198.1, 163.3, 142.1, 130.3, 129.9, 128.5, 128.4, 125.5, 113.6, 83.3, 55.4, 42.9, 27.4, 24.6, 24.5; HRMS (ESI-TOF) calcd for $C_{22}H_{27}BO_4$ $(M + H)^+$, 367.2081; found, 367.2078.

(*R*)-3-Phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1-*p*-tolylpropan-1-one (2l). Colorless oil: 33.6 mg, 96% yield, 97% ee; $[\alpha]_D^{20}$ = −42.5 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (50:1); flow rate = 0.5 mL/min; t_R = 15.3 min (minor); t_R = 24.7 min (major); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.86 (d, *J* = 8.2 Hz, 2H), 7.34−7.26 (m, 4H), 7.23 (d, *J* = 8.1 Hz, 2H), 7.19−7.11 (m, 1H), 3.53 (dd, *J* = 18.2, 10.8 Hz, 1H), 3.45−3.33 (m, 1H), 2.78 (dd, *J* = 10.7, 5.2 Hz, 1H), 2.40 (s, 3H), 1.24 (s, 6H), 1.16 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 199.3, 143.6, 142.1, 134.3, 129.1, 128.5, 128.4, 128.3, 125.5, 83.3, 43.2, 27.2, 24.6, 24.5, 21.6; HRMS (ESI-TOF) calcd for $C_{22}H_{27}BO_3$ $(M + H)^+$, 351.2132; found, 351.2137.

(*R*)-3-(Furan-2-yl)-1-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propan-1-one (2m). Colorless oil: 30.0 mg, 92% yield, 96% ee; $[\alpha]_D^{20}$ = −7.5 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (50:1); flow rate = 0.5 mL/min; t_R = 14.8 min (minor); t_R = 19.9 min (major). Other spectra and properties data matched those reported in the literature.[14]

(*S*)-1-Phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)butan-1-one (2n). Colorless oil: 24.1 mg, 88% yield, 95% ee; $[\alpha]_D^{20}$ = +12.5 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (50:1); flow rate = 0.5 mL/min; t_R = 11.1 min (*R*, minor); t_R = 15.3 min (*S*, major). Other spectra and properties data matched those reported in the literature.[6c]

(*R*)-4-Phenyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)butan-2-one. (2o). Colorless oil: 25.5 mg, 93% yield, 47% ee;

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$[\alpha]_D^{20}$ = −15.1 (*c* 0.2, $CHCl_3$) (lit.[7] $[\alpha]_D^{20}$ = −34.2 (*c* 1.06, $CHCl_3$) 92% ee (*R*)). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (100:1); flow rate = 0.5 mL/min; t_R = 14.7 min (*S*, minor); t_R = 18.0 min (*R*, major). Other spectra and properties data matched those reported in the literature.[6c]

(*R*)-4,4-Dimethyl-1-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)pentan-3-one (2p). Colorless oil: 29.7 mg, 94% yield, 97% ee; $[\alpha]_D^{20}$ = −41.5 (*c* 0.2, $CHCl_3$). The enantiomeric excess was determined by HPLC with a Chiralpak IA column: λ = 254 nm; eluent, hexane/*i*-PrOH (200:1); flow rate = 0.5 mL/min; t_R = 13.2 min (minor); t_R = 13.9 min (major). The specific rotation of the corresponding hydroxyl ketone was $[\alpha]_D^{20}$ = +58.5 (*c* 0.2, $CHCl_3$). The absolute configuration was determined by comparing this value with the reported literature[15] (lit. $[\alpha]_D^{24}$ = −32.9 (*c* 2.27, $CHCl_3$) 52% ee (*S*)). Other spectra and properties data matched those reported in the literature.[14]

■ ASSOCIATED CONTENT

Supporting Information

X-ray crystallographic data (CIF file of **7a**) and detailed spectral data for products. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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